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TITLE: POWER SUPPLY DESIGN FOR HADRON FACILITY

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POWER SUPPLY DESIGN FOR HADRON FACILITY

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Abstract

Recently, a study investigated the feasibility of building a large 60 GeV, kaon factory accelerator. This paper presents the conceptual design of the magnet power supplies and energy storage system. In this study the following three systems were investigated.

(a) power supply using storage generator.
(b) power supply using inductive storage device.
(c) resonant power supplies.

These systems were analyzed from both technical and economical points of view. It was found that all three systems are feasible and can be built using commercially available components.

From a technical point of view, the system using inductive storage is the most advantageous. The resonant power supply is the most economical solution.

A. POWER SUPPLY USING STORAGE GENERATOR

INTRODUCTION

The Advanced Hadron Facility consists of an oval shape main ring with 80 magnets connected in series. The magnets in the main ring loop have 0.068 H inductance and 0.106 ohm resistance, including the busbar inductances and resistances. The Main Ring General arrangement is shown in Fig. 1. The required magnet current is shown in Figure 2a. The calculated voltage and power needed to drive the current through the loop is shown in Figures 2b and c. This system operates with a 3.3 Hz frequency and the operation cycle is divided into four periods:

- Injection: The power supplies keep the magnet current constant at 1040A which requires low voltage and power.
- Acceleration: The power supplies increase the current rapidly from 1040 A to 10,000 A. This requires high voltage and power because the energy stored in the magnets increases from 0.37 MJ to 34 MJ.
- Flat top: The power supplies keep the magnet current constant at 10,000 A, which requires relatively low voltage and power.
- Reset: The power supplies produce large negative voltage to reduce the current and energy stored in the magnet from 10 kA or 34 MJ to 1040A or 0.37 MJ, respectively.

DESIGN CONSIDERATIONS

The magnet design studies indicate that the magnet's insulation to ground can be economically designed to withstand up to 10 kV peak voltage. This suggests that the power supplies should be distributed along the ring to keep the voltage to ground less than 10 kV.

These requirements resulted in the division of the loop into six sections as shown in Figure 1.

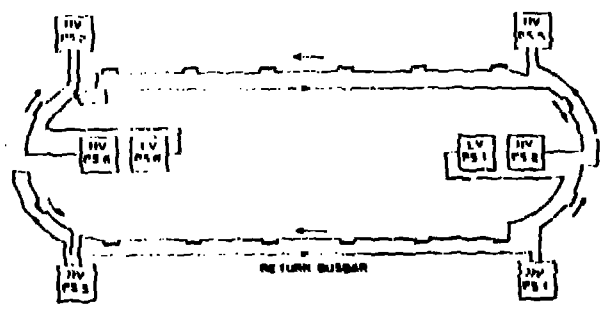

Fig. 1 Main Ring General Arrangement

Figure 2a shows that during the flat-top and injection period low voltage is needed to maintain the current. But, during the acceleration and reset period, high voltage is required to increase or decrease the current. This can be achieved by using six, high-voltage power supplies. These operate only during acceleration and reset period. They are bypassed during the injection and flat-top period, when two low voltage power supplies keep the required current constant.

During the acceleration period, the power supplies operate as rectifiers; but during reset, they operate as inverters which require full thyristor controlled bridges.

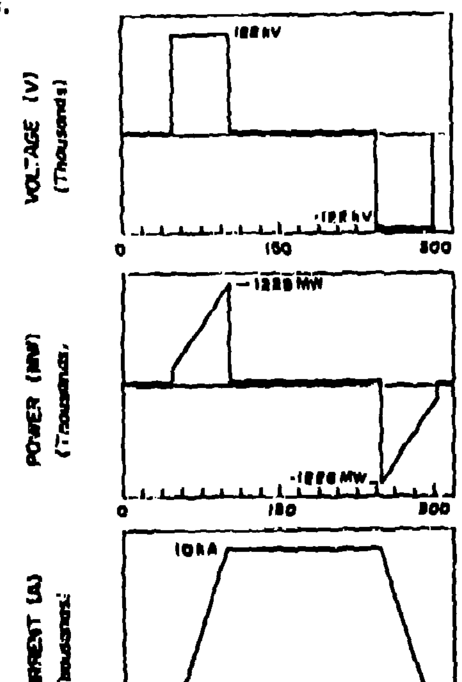

Fig. 2 Main Ring Voltage, Power and Current

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The dc current ripples disturb the beam. The permitted ripple current is less than 20 A. The system analyses shows that this can be achieved by using 24 pulse operation and capacitor filters. A further advantage is that this system can be controlled every 694 μs by adjusting the firing angle of the thyristors.

The power supplies drive variable current through the magnet loop. The magnetic field generated by the loop current may produce disturbances in electrical and electronic circuits located near the accelerator. In order to reduce or eliminate this magnetic field, the magnets will be interconnected in such a way that they form a dual loop as shown in Figure 1. In this arrangement the magnets will be connected so that the magnetic field at each magnet will be in the same direction but the external field disturbances will be minimized by providing a return current path.

During the acceleration period, the power supplies draw about 34 MJ to charge the magnets, which results in 1200 MW peak power. During the reset period, the power supplies remove 34 MJ energy from the magnets. This operation requires a large energy storage device because the local electric network is unable to supply this large pulse load. Capacitive, inductive and fly-wheel generator energy storage systems were compared.

The study indicated that at the present time the fly-wheel generator is the most economical storage device because several large surplus nuclear generators are available in the U.S.

SYSTEM DESCRIPTION

a) Power Supplies

The system will be supplied by six, high-voltage and two, low-voltage power supplies. Figure 3 and 4 show the one line diagram of a high- and low-voltage power supply. Both power supplies operate in 24 pulse mode and consist of two twelve pulse converters connected in series.

The twelve pulse converters in the high voltage power supply are built with two thyristor bridges connected in series. Each bridge is rated 5 kV, 4200A(avg). Each leg of the bridge contains a thyristor module with three liquid-cooled high voltage thyristors. The module is rated to 6 kV and 1400A (avg). The thyristors are equipped with snubber and firing circuits. Each bridge is shunted by a bypass which consists of three thyristor modules in parallel.

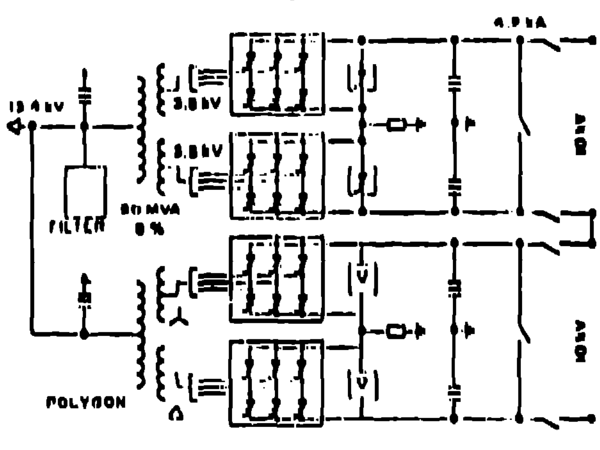

Fig. 3 HV Power Supply

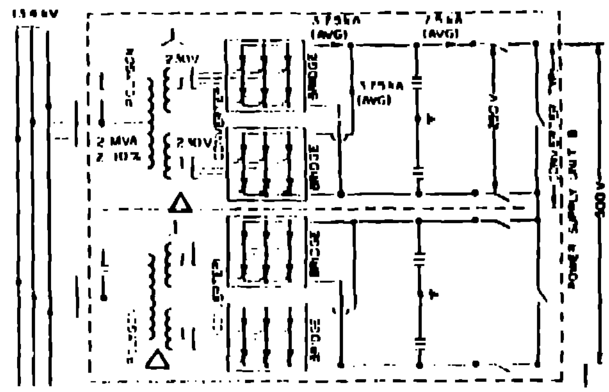

Fig. 4 LV Power Supply

The converter is protected by Metal Oxide (MOV) surge arresters and equipped with filter capacitor. The disconnect switches permit reduced power operation of the system during the maintenance or failure of a converter.

The twelve pulse converter in the low voltage power supply is built with two thyristor bridges connected in parallel. Each bridge is rated to 500 V 4200 A (avg). The bridge is built with six, high-power, liquid-cooled thyristors. It is protected by MOV surge arrestors and equipped with disconnect switches.

Both the high and low voltage converters are supplied by a polygon/delta/wye connected transformer. The secondary voltages of these converter transformer will be shifted by -7.5° and 37.5° relative to the primary voltage if supplied by positive sequence voltage. If it is supplied by negative sequence voltage the phase shift will be -22.5° and +7.5°. The converters will be connected in series and thus operate in 24 pulse mode.

The 24 pulse converter mode will produce a smooth dc current. Only two (2) 150 kVAR capacitors are needed for filtering on the dc side of each converter. Each converter generates harmonics on the ac side. These harmonics produce disturbances in the primary ac power network and may cause overheating in the fly-wheel generator. The harmonics will be reduced by filters connected directly to each converter transformer's primary terminals. Each filter will consist of a tuned circuit (for the 11th & 13th harmonics) and a high pass unit for 23rd, 25th and higher order harmonics.

b) AC System

The one line diagram of the ac system is shown in Figure 5. The system consists of a fly-wheel generator with forced excitation. The fly-wheel generator will be a surplus nuclear generator rated about 1000-1200 MW. The generator rotor has to be reinforced to permit the startup by a variable speed drive device.

The generator will be driven by a variable speed drive system, which will consist of a load commutated rectifier-inverter system. This system rectifies the voltage of the 13.4 kV, 60 Hz and the inverter converts this dc voltage to variable frequency ac voltage. The variable frequency ac starts and drives the generator as a synchronous motor. The generator speed can be adjusted accurately and the system draws constant power from the 60 Hz ac system. The power will be kept constant by the gate control of the thyristors in the rectifier/inverter circuits.

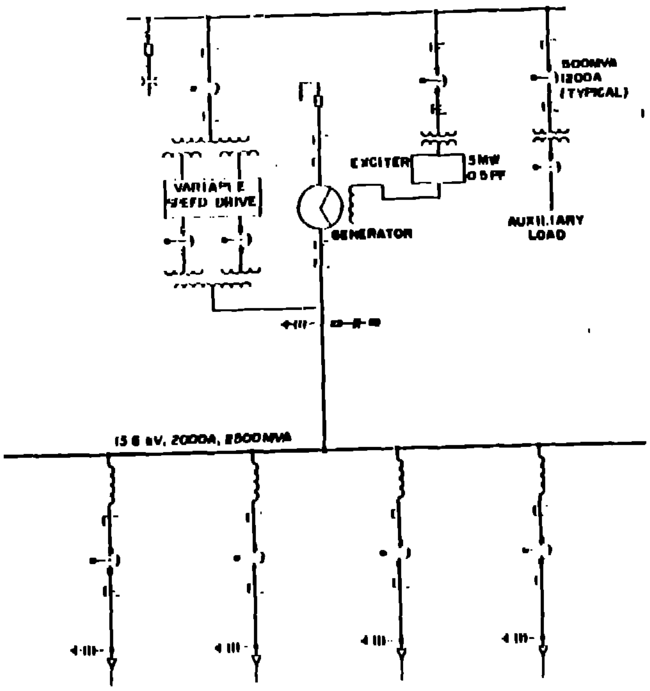

Fig. 5 Ac System with Flywheel Generator

During the acceleration period the generator together with the variable speed drive supplies the energy to all magnets through the converter systems.

During the flat top period the variable speed drive will provide energy for both the generator, which is accelerated as a motor, and for the two low voltage rectifiers supplying the magnets.

In the reset period, both the energy recovered from the magnets and the power supplied by the variable speed drive, accelerate the generator and increase the generator frequency nearly to the initial level.

During the short injection period, the variable frequency drive again supplies energy for both the magnet (through the two low voltage rectifiers) and for the generator (which is accelerated).

The constant power of this variable frequency drive will be selected in such a way that the original frequency is restored at the end of the injection period. It is estimated that the system draws more or less constant load of17 MW from the 13.8 kV 60 Hz busbar.

The one-line diagram on Fig. 5 shows that the generator and the inverter outputs will be connected to a 13.8 kV variable frequency busbar directly, i.e. without a generator circuit breaker. The magnet power supplies will be located at the six power supply buildings and they will be supplied via power cables from the variable frequency busbar. Current limiting reactors will be inserted in each power feeder to limit the short-circuit to 1000 MVA and will permit the use of standard metal enclosed switchgear.

OPERATION ANALYSES

A computer model has been developed for this study of the power supply operation. This model simulated the 24 pulse operation and confirmed that the dc current harmonics and ripples are less than the maximum permissible value, assuming proper firing. However, the firing inaccuracy may increase harmonic content and produce beam disturbance.

The study of generator operation revealed that the generator will operate in a transient mode because of the fast (50 ms) extraction of power. Transient operation increases the rotor current and induces undesirable rotor heating. This heating effect has been studied by Brown Boveroo. The study confirmed the predicted rotor current increase but showed that the 1000 MW generator will be able to operate in this mode without any danger.

COST ESTIMATE

The cost estimate of the designed system assumed that the power supplies will use standard U.S. manufactured thyristor modules. The converter transformers are similar to the transformers used at the Princeton TFTR Tokomak Fusion Reactor. The actual purchase price of the transformers were escalated. The generator was assumed to be available free of charge, therefore only the transportation, fundation and auxiliary equipment costs are included. The operation cost estimated by using the calculated system losses and the DOE recommended present value (20 years operation time) multiplier. The total estimated cost of the electric systems is $145-155M. The estimated hardware and installation cost is $95-100M. The present value of the operation maintance cost is $50-55M.

CONCLUSIONS

The electrical power system is designed for the Advanced Hadron facility acceleration. It has the following major attributes:

- The system can be built with proven, tested components
- The system operation is verified by computer analyses
- The system draws constant power from the ac network
- The design is cost effective
- The hardware and operation cost ratio is approximately two

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B. POWER SUPPLY USING INDUCTIVE STORAGE

The general system arrangement is shown in Figure 1.

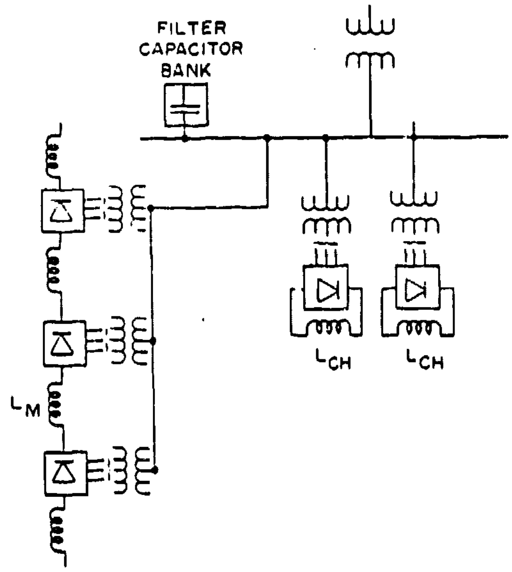

Fig. 1 Inductive Storage Concept

The main ring magnets will be supplied by six high voltage and two low voltage power supplies. These power supplies drive a trapezoid shape current wave through the magnets.

The power supplies are identical with those shown in Figures 3 and 4 in part A. The inductive energy storage devices are air cooled reactors, which are supplied by similar power supplies. During the operation, the energy is exchanged between the magnets (L_M) and inductive energy storage devices (L_{CH}). The losses are supplied from the local electric network.

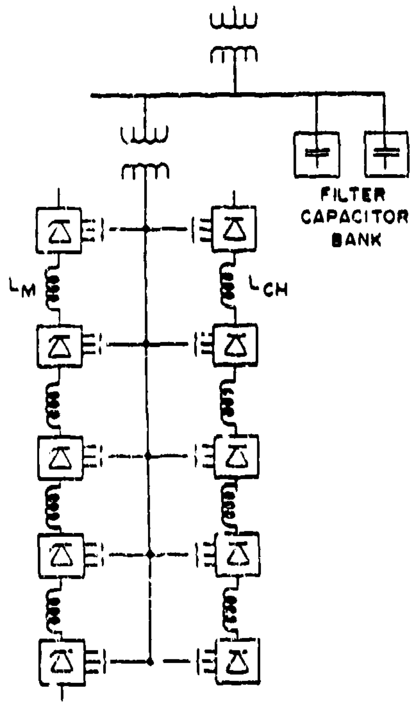

Fig. 2 Inductive Storage Using the Identical Ring

Figure 2 shows a variation of this circuit, which consists of two identical accelerators (L_M and L_{CH}). The two accelerators operate in a push-pull mode, i.e., where L_M is in the accelerator period, L_{CH} is in the reset period. Therefore, the energy from L_M is transferred to L_{CH}. This arrangement assures the high level of component utilization and economic operation.

SYSTEM OPERATION

The required magnet current, voltage and power are shown in Fig. 2 of part A.

This system operates with 3.3 Hz frequency and the operation cycle is divided into four periods:

o Injection: The magnet power supplies keep the magnet current constant at 1040 A which requires low voltage and power. The high-voltage power supplies are bypassed; only the low-voltage power supplies are operating as rectifiers. The inductive storage power supplies (L_{CH}) are operating as rectifiers and adjusting the current of L_{CH} to 10 kA.

During this period, the electrical network supplies the system loss, which is a constant load.

o Acceleration: The magnet power supplies increase the current rapidly from 1040 A to 10,000 A. This requires high voltage and power because the energy stored in the magnets increases from 0.37 MJ to 34 MJ.

All the magnet power supplies operate as rectifiers.

The inductive storage power supplies are operating as inverters, reducing the current of L_{CH} from 1040 A to 10,000 A. The energy stored here supplies the magnets. The electrical network supplies the system losses.

o Flat top: The magnet power supplies keep the magnet current constant at 10,000 A, which requires relatively low voltage and power. The high-voltage power supplies are bypassed and the low-voltage power supplies are operating as rectifiers.

The inductive storage power supplies are adjusting the current of L_{CH} to 1040 A and replacing the energy losses.

Again the electrical network is loaded with the system losses.

o Reset: The magnet power supplies produce large negative voltage to reduce the current and energy stored in the magnet from 10 KA or 34 MJ to 1040 A or 0.37 MJ, respectively.

The magnet power supplies are operating as inverters. The energy storage power supplies are operating as rectifiers. The energy stored in the magnets are transferred into the inductive storage devices (L_{CH}).

Again, the electric network is loaded by the system losses.

COST ANALYSES

The system losses were calculated using the computer program developed for the storage generator. The calculated losses are 20 MW. These are higher than the losses calculated for the storage generator because the losses in the individual storage devices are higher than in the generator. However, if the push-pull system is used their losses are divided between the two systems, which increases the system economy. The present value of the losses were calculated using the DOE recommended method. The total estimated cost of the system is around $200 M; the estimated hardware and installation cost is $135-140M, the present value of operation cost is $60-65M.

C. RESONANT POWER SUPPLY

INTRODUCTION

The Advanced Hadron Facility is a future kaon producing accelerator in Los Alamos. The particle beam is accelerated by RF cavities and directed by magnets. The main ring will be built with eighty large magnets connected in series and arranged in an oval-track shape loop. The power supplies drive the current through this loop. The required current wave shape is shown in Figure 1. The wave repetition frequency is 3.3 Hz and the wave is divided into four periods as shown in Figure 1. This wave can be efficiently generated by a resonant power supply. Several publications deal with the resonance power supply; recently W. F. Praeg [1-2] developed a circuit, which is able to generate current waves with a flat top and bottom. The purpose of this paper is the engineering design of a resonance power supply for a large, 34 MJ accelerator.

SYSTEM CONFIGURATION AND MODEL

The main ring loop of magnets will be divided into 20 sections and a high voltage resonant power supply will be connected in series with each section. This arrangement assumes that the magnet voltage to ground is 10kV or less. The conceptual one line diagram of a resonant power supply is shown in Figure 2. The system has been modeled using the Micro-Cap II computer program. The model circuit is shown in Figure 3.

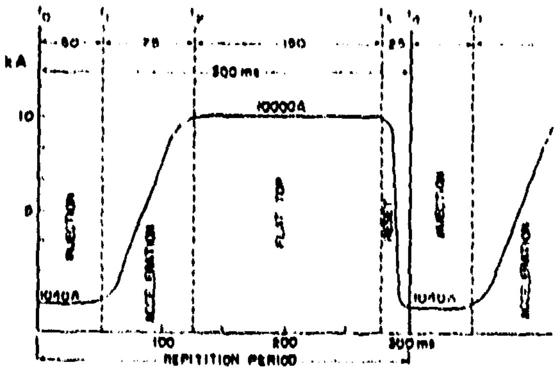

Fig. 1 Current Wave Form

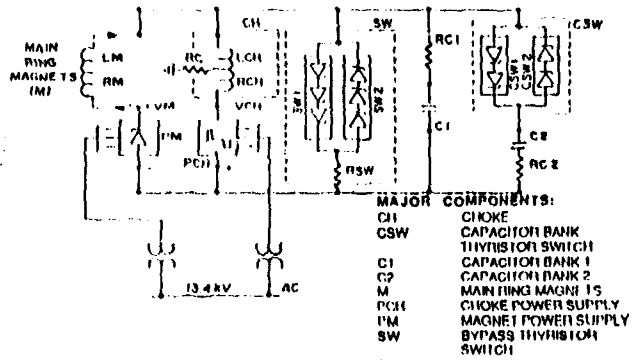

Fig. 2 Conceptual one-line diagram

The magnet and choke is modeled by an inductance and resistance connected in series. The magnet and choke power supply is modeled by two programmable voltage sources connected in series. These voltage sources are turned on during the injection and flat top period and bypassed during acceleration and reset period. The voltage source representing the choke power supply provides a short duration voltage pulse, which replaces the energy loss in the circuit.

The capacitor banks are modeled by a capacitor and a series resistance to represent the sum of the cable interconnections and bus resistances.

The by-pass thyristor switch is modeled by two switches connected in parallel. Each switch consists of an equivalent resistance, voltage source and a voltage controlled switch. The resistance and voltage source simulates the forward voltage drop of the thyristors, the voltage controlled switch simulates the turn on of the thyristors.

The capacitor bank thyristor switch is modeled by one voltage-controlled switch.

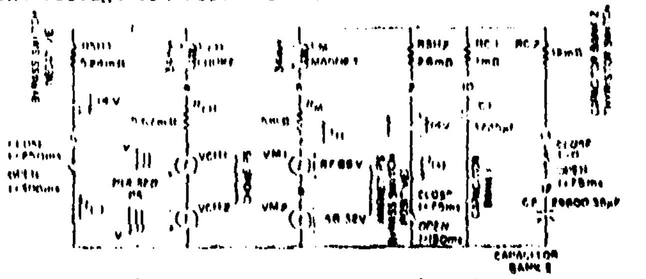

Fig. 3 Computer model circuit

ANALYSIS OF SYSTEM OPERATION

The current, voltages and losses were calculated by the MICRO-CAPII program.

In order to optimize the system operation, the parameter values have been varied until the optimum conditions were achieved.

The calculated power, voltage and current wave forms permit the analysis of the operation and allow the determination of component ratings.

Using the obtained values each major component was designed.

MAGNET POWER SUPPLY

The one line diagram of the magnet power supply is shown in Figure 4. The basic element of the system is a standard bridge converter with liquid cooling. A suitable unit is a standard thyristor assembly which rated for 600 V and 4200 A at 3 gallon/minute flow rate. This unit uses heavy duty disc thyristors.

Two units connected in parallel form a converter which operates in a twelve (12) pulse mode. This converter is supplied by a polygon/wye/delta transformer. Two of these converters are connected in series and operate in a twenty-four (24) pulse mode. The two converters connected in series form a magnet power supply which is rated at ± 500 V, 6 kA (avg), 10 kA peak.

The secondary voltages of a polygon/delta/wye connected converter transformer will be shifted by -7.5° and 37.5° relative to the primary voltage if supplied by positive sequence voltage. If it is supplied by negative sequence voltage the phase shift will be -22.5° and +7.5°.

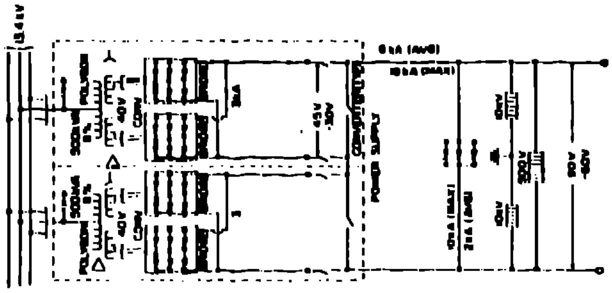

Fig. 4 Magnet Power Supply

CHOKE POWER SUPPLY

The choke power supply one line diagram is shown in Figure 5. The current regulator charges the capacitor bank through the diode bridge by constant current. The capacitor bank is discharged by thyristor switch M1 & M2 during the injection period and replaces the energy loss in the circuit. The diodes provide a current path for the inductive current and prevent over voltages.

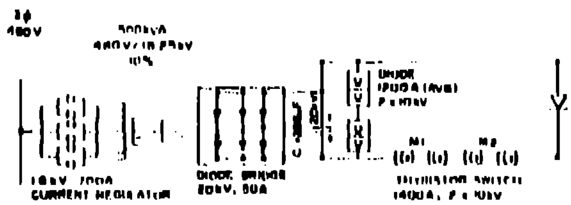

Fig. 5 Choke Power Supply

BYPASS THYRISTOR SWITCH

The computer simulation shown that the bypass switch has to conduct in both directions. The positive current flows during the flat top period and negative current during the injection period. This requires two separate thyristor switches, one for the positive (SW2) and one for the negative direction (SW1).

The positive switch turns on at the beginning of the flat top period, the negative switch at the beginning of the injection period. In both cases, before turning on, the switch voltages are practically zero and the switch diverts about 9kA current from the capacitor bank into the switch.

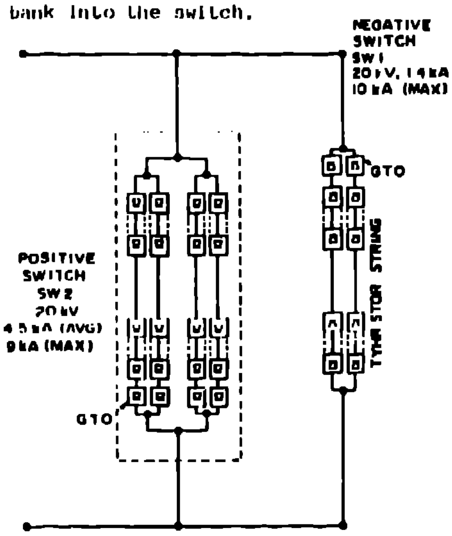

Fig. 6 Bypass thyristor switch

At the end of their respective periods, both switches turn off and the switch current is diverted into the large capacitor bank connected in parallel. In both cases the recovery voltage increases slowly. This permits the use of gate turn off (GTO) devices for the current interruption.

The building block of the is a switch-unit which consists of two thyristor modules and a gate- turn off switch (GTO) modules connected in series.

The thyristor module is built with five water cooled high voltage thyristors and rated to 10kV and 1400 Arms. The GTO switch consists of two water cooled GTO devices connected in parallel and rated 1000V and 1400A.

A MOV (metal oxide varistor) and a RC Snubber circuit is connected in parallel with each device to equalize the voltage distribution and reduce overvoltages. Each device has a gate circuit. The positive switch has four, the negative has two units connected in parallel. Both the thyristors and the GTO's are triggered simultaneously when the switch is turned on. The switch is turned off by the GTO devices which interrupt the switch current within a few microseconds.

The slow rising recovery voltage permits the deionization of the thyristors and the blocking of the 20 kV peak recovery voltage.

CAPACITOR BANKS

Each resonance power supply has two capacitor banks. The design data are shown in Table 1:

Table 1. CAPACITOR BANKS RATING

	Bank 1	Bank 2
Numbers	20	20
C	3725 μF	29800 μF
V_{peak}	20 kV	10 kV

The capacitors bank will be divided into five capacitor bank units. Each unit consists of up to 200 capacitor cans, each can is rated for 400 kVAR and 20 kV or 300 kVAR and 10 kV. The capacitors are single phase (one bushing) standard distribution type units. Each capacitor can is equipped with current limiting fuses. The fuses are rated to withstand a current of 15 kA peak as well as provide protection to prevent the rupture of the cans in the event of capacitor short circuit.

The capacitor bank units have five vertical racks bolted together. The aluminum structure serves as a current return path. Each unit will be mounted on six post type 15 kV insulators.

The capacitors are connected in parallel with bus bars rated 8000 A rms.

CAPACITOR BANK THYRISTOR SWITCH

The bi-directional switch operates only during the acceleration period and conducts current in both directions. The switch has a positive and a negative branch. The positive branch consists of two thyristor modules connected in series. These modules are similar to those used in the bypass switch. The negative branch is built with two diode modules connected in series.

The CSW2 switch is turned on when the acceleration period starts. The switch connects the Capacitor Bank 2 (C2) in parallel with Capacitor Bank 1 (C1). The opening of bypass switch (SW2) will divert the magnet and choke current to the capacitors. The capacitor current reaches the -9 kA level very rapidly and then the current increases to the 9 kA level following a cosine curve. When the current polarity changes the CSW2 switch, it turns off and the current flows through the diode modules.

When the current reaches 9 kA, the bypass switch turns on. This diverts the current from the capacitor bank to the bypass switch. The Capacitor Bank current will then reduce rapidly.

AC SYSTEM

The ac system consists of a main substation and twenty distribution substations. The main substation will be supplied from the 115 kV line through a 60 MVA, 115/13.8 kV transformer. The switchgear will be standard 13.8 kV metal clad switchgear with six bays. Five (5) bays will be equipped with circuit breakers and the sixth will be equipped with potential transformers and metering.

The twenty distribution stations will be distributed along the main magnet loop. Two ring feeders from the main station switchgear will feed the distribution stations.

TABLE 2
AC System Load

	P(MW)	Q(MVAr)	S(MVA)	Duration (ms)
INJECTION	14.22	2.72	14.47	50
ACCELERATION	15.43	0.41	15.43	75
FLAT TOP	33.00	13.38	37.77	150
RESET	15.43	0.41	15.43	25

OPERATIONAL ANALYSIS

The system operation has been analyzed and the maximum load has been calculated. The analyses revealed that the system requires reactive power compensation and harmonic filtering. A 12 MVAr filter is selected, and connected to the main substation bus bar. The AC system load is shown in Table 2.

Table 2 indicates that during the flat top period the system will load the local ac network with an 18MW, 150ms duration pulse, which may produce disturbances.

COST ESTIMATE

The cost estimate of the designed system assumed that the power supplies, switches will use standard U.S. made thyristor modules. The operation cost estimated by using the calculated system losses and the DOE recommended present value (20 years operation time) multiplier. The total estimated cost of the electric systems is $125-130M. The estimated hardware and installation cost is $75-80M. The operation cost is $50-55M.

CONCLUSION

The engineering design of the electric system of the main ring power supplies shows that:

- The resonant power supply can be built with standard commercially available components.
- The most critical component is the bypass switch, which requires gate turn off thyristors (GTO) connected in parallel.
- Standard metal clad switchgear can be used for the AC system.
- The resonant power supplies can be fed directly from the 115 kV utility network. But the resonance power supplies draw pulse-loads from the utility network. The 18MW, 150 ms duration pulse may produce disturbances.
- AC filter and reactive power compensation is needed for economic operation.

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D. EVALUATION

The three systems were compared from the technical and economical point of view. The results are summarized in Tables 1 and 2.

TABLE 1.

TECHNICAL PERFORMANCE COMPARISON

	Thyristor Converter and Storage Generator	Inductive Storage	Resonant PS
Peak power loading	15 MW	15 MW	35 MW
Power fluctuations	None	None	20 MW
Operation experience	Good	None	None
Reliability	Medium	Good	?
Maintenance	High	Low	Medium
Reactive power consumption	5 MVA	5 MVA	20 MVA
Loss MW	17.1	20	17.00
Control	Good	Easy	Difficult

Table 1 shows that the inductive storage system is most advantageous in technical point of view; except the higher losses. Particularly advantageous is that this system requires a simple control and all components are available commercially. Both the air cooled inductances and the inverter/rectifiers are well developed and tested equipment.

The disadvantage of the resonant power supply is the pulse loading of the electric network.

TABLE 2

COST COMPARISON

	Thyristor Converter and Storage Generator	Inductive Storage	Resonant PS
Hardware	\$ 97.06 M	\$140 M	\$ 77.80 M
Operation	\$ 51.45 M	\$ 60 M	\$ 51.00 M
TOTAL	\$148.5 M	\$200 M	\$128.8 M

The cost comparison shows that the most economical system is the Resonant Power Supply. The cost of inductive storage devices becomes attractive if the push-pull system with two identical rings are used.

CONCLUSION

1. All the three systems are suitable for the Kaon factory accelerator.
2. Each system can be built with mostly standard commercially available components.
3. The most critical component is the bypass switch in the Resonant Power Supply, because this switch requires gate turn off (GTO) thyristors connected in parallel.
4. Standard metal clad switch gear can be used for the ac system.
5. The system with storage generator or inductive storage produces constant load on the ac system. Resonant Power Supply draws pulse loads from the utility network. The 18 MW 150 ms pulse may produce disturbances.
6. The pulse loading of the storage generator produces rotor heating which will require further investigation.
7. The most economical system is the Resonant Power Supply.